ARMY RESEARCH LABORATORY

Analysis of Three UH-60 Blackhawk Servolink Components P/N 70400-08110-061

by Marc Pepi, Victor Champagne, Daniel Snoha, Scott Grendahl, and James Catalano

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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Weapons and Materials Research Directorate, ARL

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1. Objectives

(1) To determine if any of the three servolinks contained areas that were not shot peened.

(2) To determine by x-ray diffraction (XRD) analysis if any surface anomalies adversely affected the compressive residual stresses imparted by shot peening.

2. Conclusions

(1) Servolinks serial numbers (S/N's) 01171, 01266, and 01268 did not show any areas on the surface that were completely void of dimples, indicating that shot peening had not been accomplished. However, the shot-peened surface was not uniform in appearance.

(2) The residual stress profile measurements of heavily dimpled areas as compared to those taken on lightly dimpled and/or scratched areas were similar and acceptable having compressive stress values associated with that of a normal shot-peened surface. The XRD analysis did not reveal any unacceptable values of compressive residual stress.

3. Background

The shot-peened surfaces of three UH-60 servolinks (S/N's 01171, 01266, and 01268) were examined at the request of the Aviation and Missile Command (AMCOM). The U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD, performed visual and stereoscopic examination of the shot-peened surface of the servolinks and measured the depth of surface scratches using an optical microscope. In addition, x-ray diffraction was utilized to measure the compressive residual stresses on various suspect areas of the shot-peened surface. A representative servolink is shown in Figure 1 with the topcoat of paint removed, revealing the cadmium-plated surface. According to an e-mail message from Mr. Darrell Hutson [1], Aviation Research, Development, and Engineering Center (AVRDEC) to Aviation and Missile Research, Development, and Engineering Center (AMRDEC) personnel—the following scenario is believed to have caused the surface scratches noted on the parts:

> I talked with Tom Daily, QA manager at Alken. He received a copy of the conformance Inspection report and is very concerned. Mr. Dailey [sic] went to Dayton T. Brown and looked at the part we inspected. He then returned to his facility and investigated his

parts in house. Alken had two of the parts in house in MRB status. The parts were in MRB for faulty bearings adhesive. The following is what he believes happened to our specimen. The shot-peening source did shot peen the -109 configuration as required. Alken then inserted the bearings with adhesive as required by the drawings. Some of the adhesive was squeezed out on the outside of the surfaces and not cleaned off before curing. The next step requires a line reaming operation. Because the line reamer must be squarely positioned against the surface of the -109 the excess adhesives must be removed. Mr. Daily believes that the technician used a stone to remove the excess adhesive and in the process removed some of the shot-peening. Mr. Daily stated that he will make available the 2 MRB parts for examination by the government if we need them.

4. Visual Examination—Verification of Shot Peening

To the unaided eye, the parts appeared to have a non-uniform shot-peened surface; in other words, some regions appeared to have a more pronounced dimpled topography than other regions. In general, the 1.125-in diameter exhibited the most pronounced dimples, while the region adjacent to the bearing raceway contained less pronounced dimples. However, as Figures 2 and 3 show, each of the areas was indeed shot peened, and they contained dimples. Figures 4 and 5 show these representative areas at higher magnification. Each servolink showed evidence of peening on the entire outer surface.

5. Visual Examination—Determination of Peening Over Scratches

Stereoscopic examination was utilized to determine whether the surface scratches observed on the components were induced prior to or after the peening operation. Figure 6 shows two of the larger scratches noted on the surface of servolink 02168, labeled as 1 and 2. Scratches 1 and 2 are shown in Figures 7 and 8 under higher magnification. Further magnification was necessary to determine whether the scratches were present prior to or after the peening process. Figures 9 and 10 show the scratches at a magnification suitable for such an analysis. From these figures, it is clear that the scratches were present prior to peening. This conclusion was drawn based upon the amount of deformation around the scratch caused by the dimpling of the shot impacts. This was generally the case with many of the scratches observed; however, there were groups of scratches found on both the 01266 and 01268 servolinks adjacent to the

bearing where this was not the case. Figures 11 and 12 show this area at low magnification. At higher magnification (Figures 13 and 14), the scratches did not appear to be deformed by the peening operation. In fact, the scratches seemed to smear the peened dimples such as to eliminate evidence of prior peening. Upon closer examination, however, peened dimples could be observed distributed sporadically among the scratches. Aside from these localized areas, ARL did not find evidence of any other scratches induced after the peening process.

6. Depth of Scratches

The depth of the deepest scratches (as determined optically) on two of the servolinks was measured using the general guidelines of ASTM G46, "Standard Practice for Examination and Evaluation of Pitting Corrosion" [2]. The microscopical method was utilized with a Nikon Epiphot 300 metallograph. A magnification of 200× was used to determine the scratch depth. For the actual measurement, the bottom of the scratch was brought into focus, followed by the surface of the servolink adjacent to the scratch. The number of increments between the focusing planes (1 increment = 1 μm or 0.001 mm) was recorded, which was converted to scratch depth. In general, the scratches on servolink 02168 were deeper than those on servolink 02166. The two scratches on servolink 02168 previously identified as 1 and 2 in Figure 6 were measured, since these appeared the deepest. In addition, scratches on the 02166 servolink were also measured. Table 1 contains the results of the scratch depth measurement. As listed, the scratch depths averaged approximately 0.0004 in, and no measurement recorded a depth greater than 0.001 in.

7. Machining Marks

Parallel sets of fine machining marks were observed on the flat-machined sections of the servolinks. They were most pronounced on the clevis end of S/N 01171. However, they appeared to be shallower than the surface scratches and were not considered significant enough to be measured. In addition, the geometry of the component prohibited such measurements.

8. Residual Stress Measurements

8.1 Experimental Procedures

Shot peened-induced residual stress was characterized on servolinks 01171, 01266, and 01268. XRD residual stress measurements were performed initially on the cadmium-plated surface and then on the shot-peened surface after

dissolving away the plating with a mixture of 30-g ammonium nitrate in 225-mL water. Subsurface residual stress was measured incrementally to an overall depth of approximately 0.014 in (0.356 mm). Material layers were removed by electropolishing with a solution of 73% methanol, 10% 2-butoxy-ethanol, 9% water, and 8% perchloric acid. Figure 1 shows the general locations where residual stress measurements were taken on each of the servolinks. The areas were chosen to represent a variety of conditions observed on the surface of the parts and can be briefly described as well-pronounced dimples, shallow dimples, machine marks, and scratches. The second objective of this study was to identify these areas of concern and document them by photomacrographs and subsequently perform XRD analysis to measure the surface and subsurface compressive stresses. This experimental procedure was designed to record and evaluate visually the shot-peened surface and to determine whether the anomalies observed adversely affected the compressive residual stresses imparted by the shot-peening process.

All XRD residual stress (strain) data were obtained utilizing the $\sin^2\psi$ stress-measuring technique in accordance with Society of Automotive Engineers (SAE) J784a [3]. The pertinent instrument fixturing and data collection parameters were CrK_α radiation diffracted from the (211) lattice planes of the body centered cubic (BCC) structure, a fixed location position-sensitive proportional counter, a 3-mm-round irradiated area, and a four-positive ψ angle arrangement. On occasion, a 7- or 10-Ψ angle arrangement employing both positive and negative ψ angles was applied to check for shear strains and strain gradients. The x-ray elastic constant ($E/1+\upsilon$, where E is Young's modulus and υ is Poisson's ratio) used in calculating the macroscopic residual stress from the measured strain was a bulk value taken from handbooks or published literature. Bulk constants represent average elastic properties for all crystallographic directions and may be different from those experimentally determined for a particular set of planes. The accuracy of measuring residual stress with x-rays is largely dependent on the elastic constant. The residual stress error (precision) for all measurements was ±1.8 ksi (±12 MPa). This value is the average of the larger of either the counting statistics stress error (from the statistical nature of the x-rays counted in the detector and from various aspects of the x-ray optics of the instrument) or the probable error (due to metallurgical and stress effects). An additional contribution to the residual stress error may result from inaccurate sample positioning and/or instrument misalignment. Using a powdered metal zero-stress standard in accordance with ASTM Specification E915 [4], this systematic error was determined to be −1.9 ksi (−13.0 MPa). All $\sin^2\psi$ plots were linear (no observed ψ-splitting or curvature), suggesting that the strain distribution was homogeneous and that the assumption of a biaxial stress state was valid. Information on the theory of XRD and the principles of XRD residual stress analysis is available from Klug and Alexander [5], Cullity [6], Hilley [3], Noyan and Cohen [7], and from the *Proceedings of the Annual Conference on Applications of X-ray Analysis* (2000) [8].

8.2 Results and Discussion

The observed (measured) surface and subsurface residual stress and stress error, measurement location and direction, and the x-ray diffraction peak width data acquired during this investigation are listed in Table 2. The residual stress data was subsequently corrected for the differences in the depths penetrated by the x-ray beam, for subsurface stress gradients, and for stress relaxation resulting from material removal by electropolishing. The x-ray peak full-width half-maximum (FWHM), or line broadening, data reported in degrees was obtained at the $\psi = 0°$ angular position. This supplemental residual stress analysis information can be used as a qualitative assessment of process-induced cold work into the material (e.g., from shot peening). Included in the Appendices are the depth analysis reports and the individual plots of true (corrected) residual stress vs. depth from the surface for the two locations each measured on the three servolinks. Figure 15 shows an example of the location of surface residual stress measurements on a heavily scratched area. The circle denotes the irradiated area (3-mm diameter). A plot of these six depth profiles is presented in Figure 16.

Compressive residual stress was measured on the surface of the servolinks after dissolving away the cadmium plating. Measurements were performed at locations without scratches as well as on or adjacent to heavily scratched areas. These surface stresses averaged -91.5 ± 4.5 ksi (-631 ± 31 MPa) and ***indicate that the scratches had little or no effect on the prior shot peening-induced residual stress***. From just beneath the surface to a depth of approximately 0.004 in (0.102 mm), a fairly uniform compressive stress averaging -101 ksi (-696 MPa) was measured. Below the 0.004-in (0.102-mm) depth, a steep stress gradient extending to approximately 0.008 in (0.203 mm) was observed in which the residual stress magnitude decreases from the maximum compressive stress measured to zero or slightly tensile. These latter residual stress levels are consistent to the final electropolished depth of approximately 0.014 in (0.356 mm). The clevis end and bearing end residual stress depth profiles for servolinks 01171 and 01268 are reasonably uniform in all respects, including the magnitude and depth of the maximum compressive stress and the total depth of the compressive layer. On servolink 01266, however, the maximum compressive stress was measured at an approximately 0.002 in (0.051 mm) deeper layer than on servolinks 01171 and 01268. Additionally, the clevis end depth profile lies to the right of the bearing end profile (on Figure 16) indicating that the beneficial compressive residual stresses extend deeper into the component.

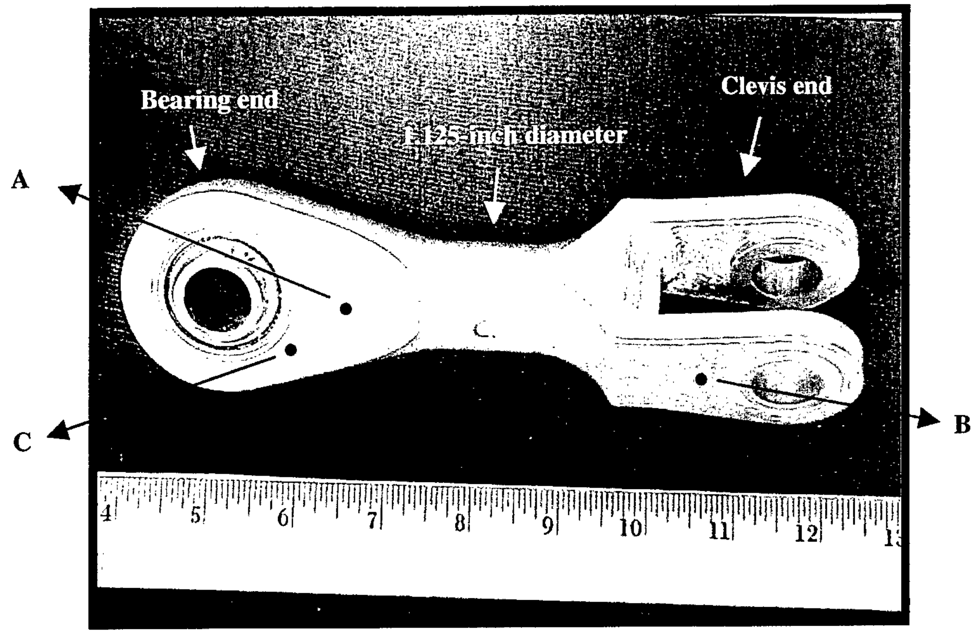

Figure 1. As-received UH-60 servolink S/N 02168. The labeling is included for clarification throughout the context of the report. Locations A, B, C, and D were areas of residual stress measurement (see Table 2). Reduced ~50%.

Figure 2. Macrograph representative of the "well-pronounced shot-peening dimples." Magnification 11.75×.

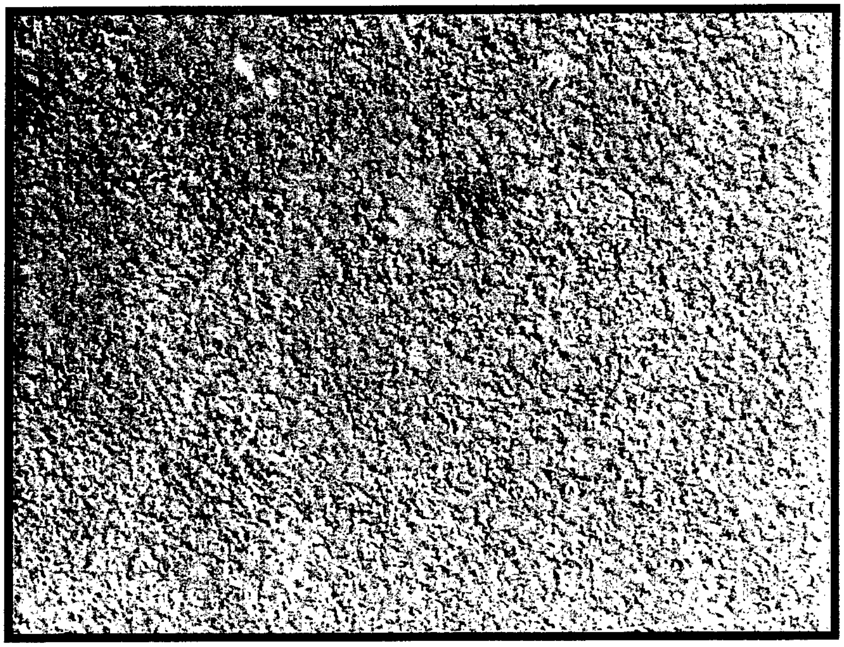

Figure 3. Macrograph representative of the "fine dimples." Also note regions appear less dimpled. Magnification 11.75×.

Figure 4. Magnified view of Figure 2 ("well-pronounced shot-peening dimples"). Magnification 56×.

Figure 5. Magnified view of Figure 3 ("fine dimples"). Note the regions that appear less dimpled. Magnification 56×.

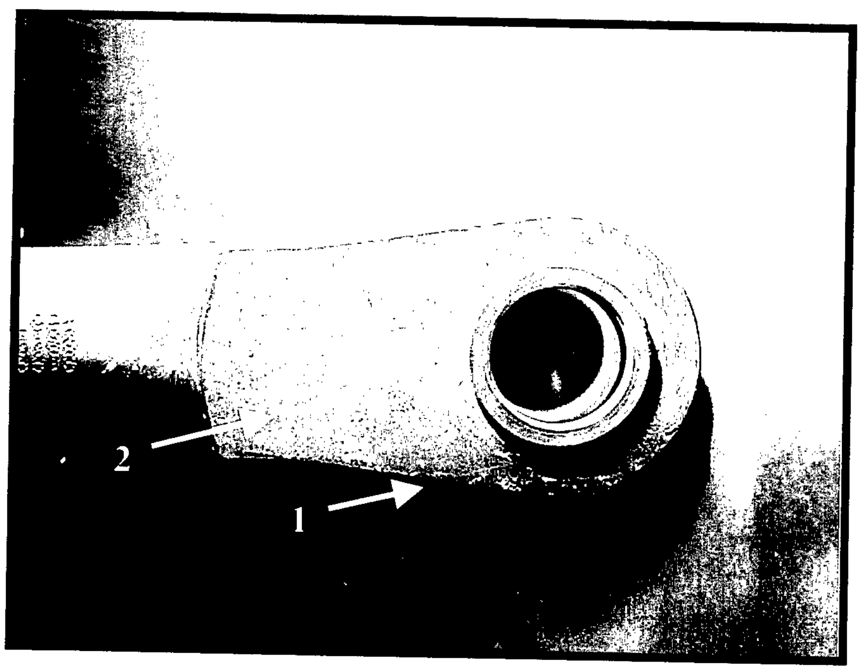

Figure 6. Clevis end of servolink 02168 showing two of the many scratches (1 and 2 as shown with arrows). Magnification 1×.

Figure 7. Scratch 1 at higher magnification. Magnification 11.75×.

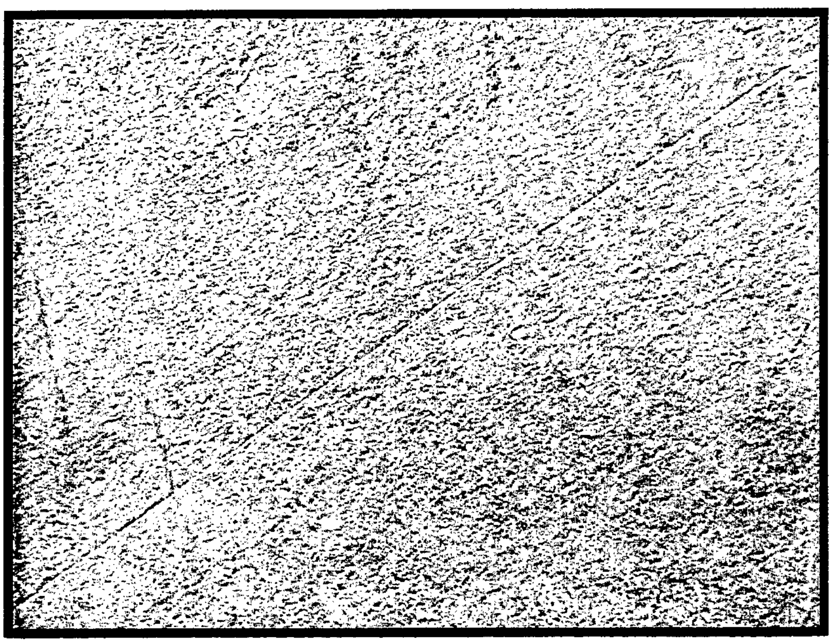

Figure 8. Scratch 2 at higher magnification. Magnification 11.75×.

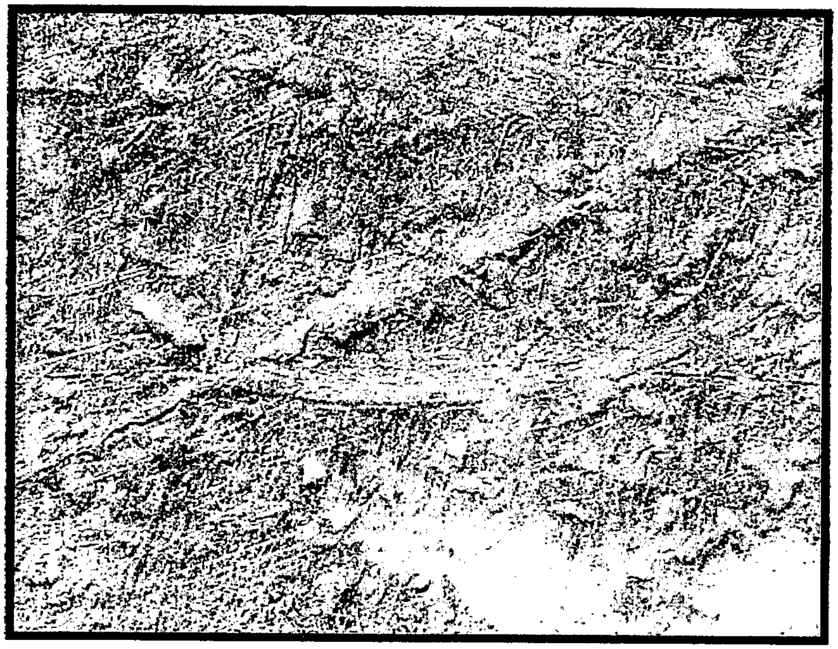

Figure 9. Scratch 1 at further higher magnification showing the effect of being shot peened. Magnification 56×.

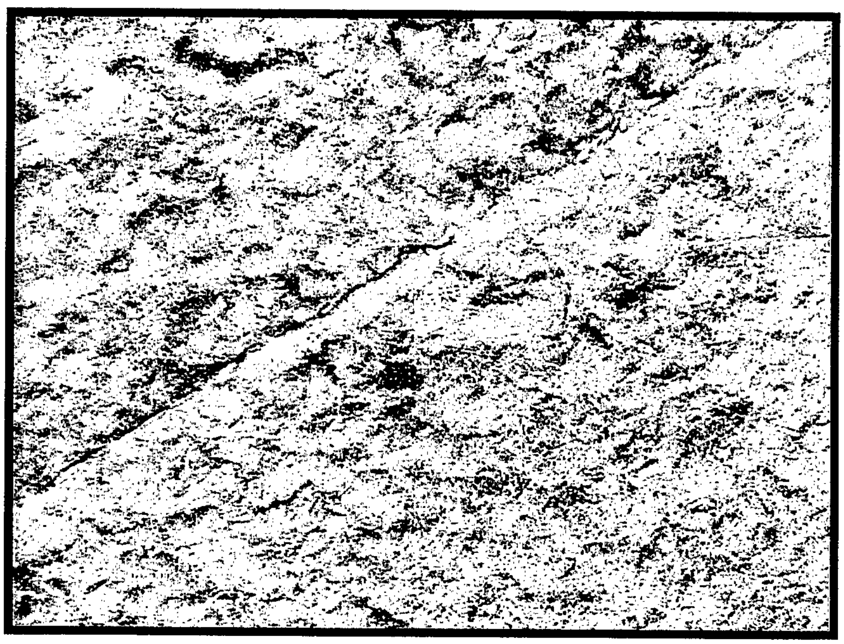

Figure 10. Scratch 2 at further higher magnification showing effect of being shot peened. Magnification 56×.

Figure 11. Scratches adjacent to the bearing on servolink 01266. Magnification 11.75×.

Figure 12. Scratches adjacent to the bearing on servolink 01268. Magnification 11.75×.

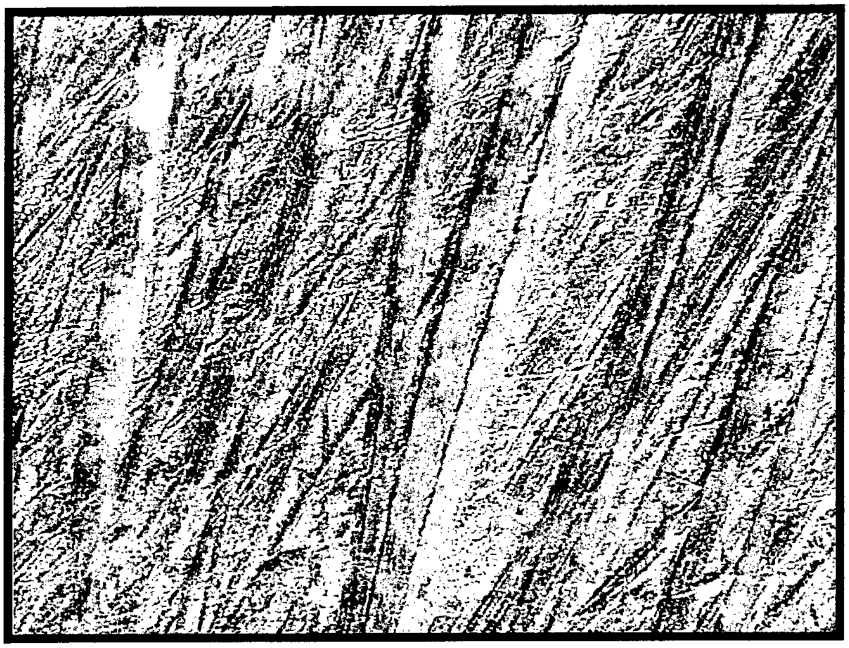

Figure 13. Scratches adjacent to the bearing on servolink 01266 at higher magnification. These scratches did not appear to have been shot peened. Magnification 56×.

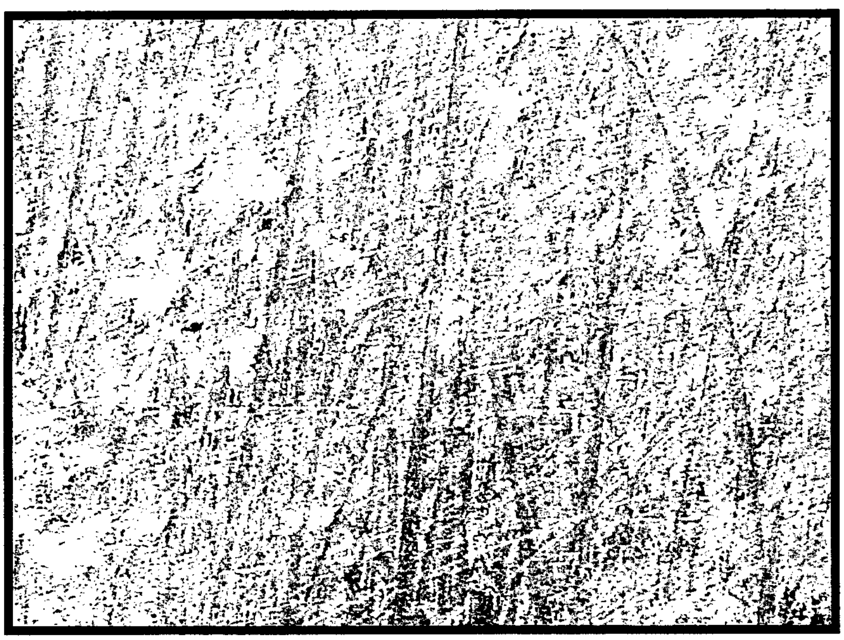

Figure 14. Scratches adjacent to the bearing on servolink 01268 at higher magnification. These scratches did not appear to have been shot peened. Magnification 56×.

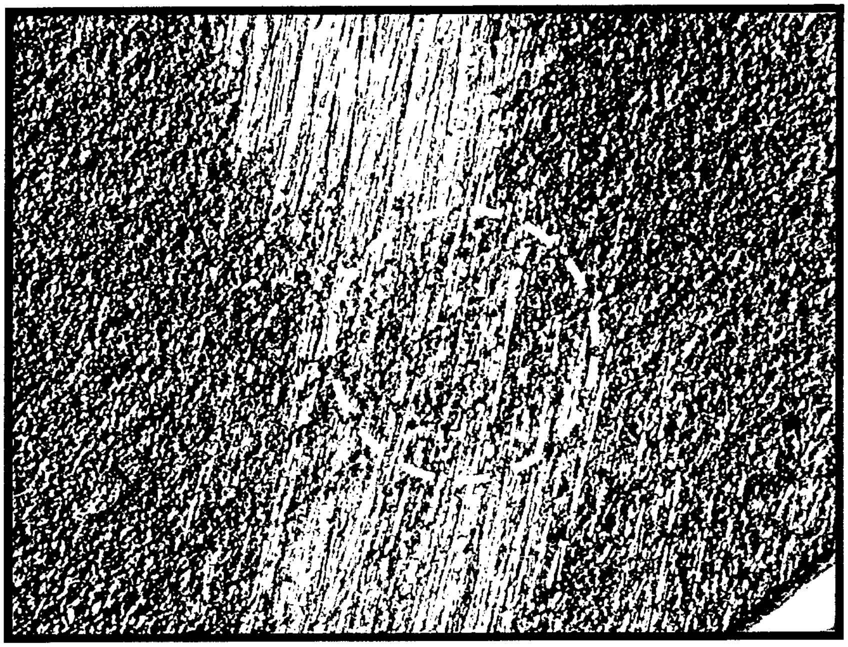

Figure 15. Macrograph showing the location of residual stress measurement within a heavily scratched area. Circle shows approximate location of residual stress depth measurements. Magnification 11.75×.

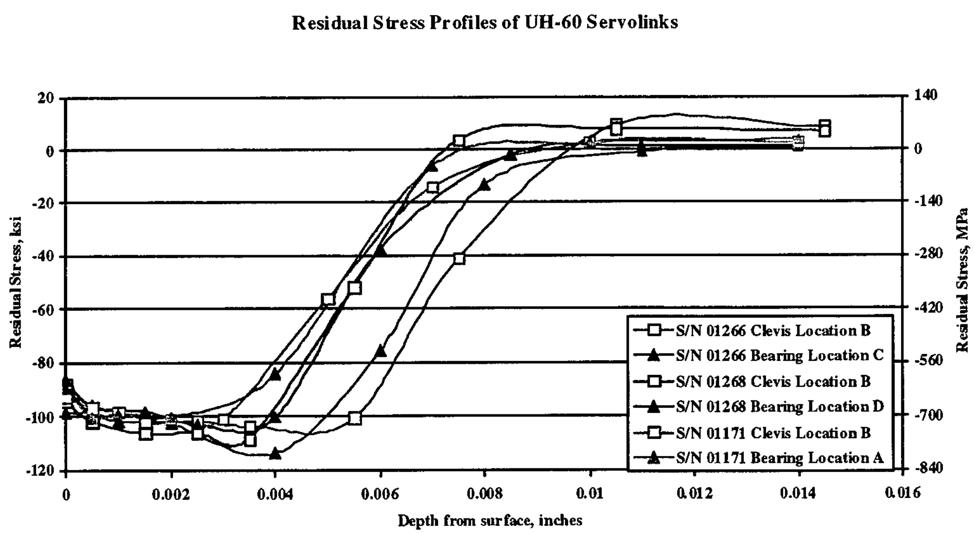

Figure 16. A plot of the six depth profiles representing corrected residual stress vs. depth for the two readings on each of the three servolinks measured.

Table 1. Depth of servolink scratches at clevis end, 1 increment = 0.001 mm.

Servolink 02166				Servolink 02168			
Side 1 of Clevis		Side 2 of Clevis		Scratch 1		Scratch 2	
Increments	Depth (in)	Increments	Depth (in)	Increments	Depth (in)	Increments	Depth (in)
5	0.00020	6	0.00024	12	0.00047	10	0.00039
4	0.00016	4	0.00016	8	0.00031	10	0.00039
6	0.00024	6	0.00024	9	0.00035	22	0.00087
10	0.00039	6	0.00024	9	0.00035	7	0.00028
12	0.00047	5	0.00020	8	0.00031	11	0.00043

Table 2. Results of residual stress measurement.

Servolink S/N	Area Measured[a]	Depth (in)	Measure Direction	Condition	Figures	Residual Stress, ksi (MPa)	Stress Error, ± ksi (MPa)
01171	A	Cd Surface	Rad.	Well Pronounced Dimples	2 and 4	-50.0 (-345)	2.6 (18)
01171	A	Surface	Rad.	Well Pronounced Dimples	2 and 4	-92.9 (640)	2.0 (14)
01171	A	0.0005	Rad.	Well Pronounced Dimples	2 and 4	-102.4 (-706)	2.3 (16)
01171	A	0.001	Rad.	Well Pronounced Dimples	2 and 4	-99.1 (-684)	2.2 (15)
01171	A	0.002	Rad.	Well Pronounced Dimples	2 and 4	-100.7 (-694)	1.3 (9)
01171	A	0.004	Rad.	Well Pronounced Dimples	2 and 4	-83.2 (-574)	1.3 (9)
01171	A	0.007	Rad.	Well Pronounced Dimples	2 and 4	-6.6 (-46)	1.4 (10)
01171	A	0.010	Rad.	Well Pronounced Dimples	2 and 4	-0.6 (-4)	1.5 (11)
01171	A	0.014	Rad.	Well Pronounced Dimples	2 and 4	0.5 (4)	0.8 (5)

[a]See Figure 1.

Table 2. Results of residual stress measurement (continued).

Servolink S/N	Area Measured[a]	Depth (in)	Measure Direction	Condition	Figures	Residual Stress, ksi (MPa)	Stress Error, ± ksi (MPa)
01171	B	Cd Surface	Long.	Machine Marks	6 and 7	-86.9 (-599)	1.9 (13)
01171	B	Surface	Long.	Machine Marks	6 and 7	-94.4 (-651)	1.7 (12)
01171	B	0.0005	Long.	Machine Marks	6 and 7	-98.1 (-677)	1.4 (10)
01171	B	0.001	Long.	Machine Marks	6 and 7	-100.2 (-691)	1.7 (12)
01171	B	0.002	Long.	Machine Marks	6 and 7	-103.4 (-713)	2.0 (14)
01171	B	0.003	Long.	Machine Marks	6 and 7	-101.5 (-700)	1.9 (13)
01171	B	0.005	Long.	Machine Marks	6 and 7	-56.6 (-391)	2.5 (17)
01171	B	0.007	Long.	Machine Marks	6 and 7	-17.1 (-118)	2.0 (14)
01171	B	0.010	Long.	Machine Marks	6 and 7	-2.8 (-19)	1.1 (8)
01171	B	0.014	Long.	Machine Marks	6 and 7	-3.5 (-24)	2.0 (14)
01266	C	Cd Surface	Rad.	Scratches	11–14	-37.9 (-261)	2.5 (17)
01266	C	Surface	Rad.	Scratches	11–14	-98.8 (-681)	3.0 (21)
01266	C	0.0005	Rad.	Scratches	11–14	-99.4 (-686)	1.6 (11)
01266	C	0.001	Rad.	Scratches	11–14	-103.0 (-711)	2.1 (15)
01266	C	0.002	Rad.	Scratches	11–14	-104.8 (-723)	1.7 (12)
01266	C	0.004	Rad.	Scratches	11–14	-114.8 (-792)	1.9 (13)
01266	C	0.006	Rad.	Scratches	11–14	-74.4 (-513)	2.1 (14)
01266	C	0.008	Rad.	Scratches	11–14	-14.2 (-98)	1.2 (9)
01266	C	0.011	Rad.	Scratches	11–14	-5.1 (-35)	1.2 (8)
01266	C	0.014	Rad.	Scratches	11–14	-3.6 (-25)	1.2 (8)
01266	B	Cd Surface	Long.	Fine Dimples	3 and 5	-6.9 (-48)	2.7 (19)
01266	B	Surface	Long.	Fine Dimples	3 and 5	-91.6 (-632)	1.8 (12)
01266	B	0.0005	Long.	Fine Dimples	3 and 5	-101.6 (-701)	1.4 (10)
01266	B	0.0015	Long.	Fine Dimples	3 and 5	-104.1 (-718)	2.4 (17)
01266	B	0.0025	Long.	Fine Dimples	3 and 5	-104.8 (-722)	2.0 (14)
01266	B	0.0035	Long.	Fine Dimples	3 and 5	-107.4 (-741)	1.3 (9)
01266	B	0.0055	Long.	Fine Dimples	3 and 5	-103.5 (-714)	1.3 (9)
01266	B	0.0075	Long.	Fine Dimples	3 and 5	-44.0 (-304)	1.6 (11)
01266	B	0.0105	Long.	Fine Dimples	3 and 5	2.7 (19)	1.6 (11)

[a]See Figure 1.

Table 2. Results of residual stress measurement (continued).

Servolink S/N	Area Measured[a]	Depth (in)	Measure Direction	Condition	Figures	Residual Stress, ksi (MPa)	Stress Error, ± ksi (MPa)
01266	B	0.0145	Long.	Fine Dimples	3 and 5	0.1 (1)	1.7 (12)
01268	C	Cd Surface	Rad.	Scratches	11-14	-61.0 (-421)	3.4 (24)
01268	C	Surface	Rad.	Scratches	11-14	-89.2 (-615)	1.8 (12)
01268	C	0.0005	Rad.	Scratches	11-14	-98.0 (-676)	1.4 (10)
01268	C	0.0015	Rad.	Scratches	11-14	-99.8 (-688)	2.9 (20)
01268	C	0.0025	Rad.	Scratches	11-14	-104.7 (-722)	2.2 (15)
01268	C	0.004	Rad.	Scratches	11-14	-99.1 (-683)	2.7 (18)
01268	C	0.006	Rad.	Scratches	11-14	-36.3 (-251)	3.0 (21)
01268	C	0.0085	Rad.	Scratches	11-14	-4.2 (-29)	1.2 (8)
01268	C	0.011	Rad.	Scratches	11-14	-2.5 (-17)	1.2 (8)
01268	C	0.014	Rad.	Scratches	11-14	-2.2 (15)	1.1 (8)
01268	B	Cd Surface	Long.	Fine Dimples	3 and 5	-15.6 (-107)	2.9 (20)
01268	B	Surface	Long.	Fine Dimples	3 and 5	-97.0 (-669)	1.7 (12)
01268	B	0.0005	Long.	Fine Dimples	3 and 5	-104.1 (-718)	2.0 (14)
01268	B	0.0015	Long.	Fine Dimples	3 and 5	-108.3 (-747)	1.8 (12)
01268	B	0.0025	Long.	Fine Dimples	3 and 5	-108.8 (-750)	1.7 (12)
01268	B	0.0035	Long.	Fine Dimples	3 and 5	-109.4 (-755)	1.4 (10)
01268	B	0.0055	Long.	Fine Dimples	3 and 5	-52.0 (-359)	2.2 (15)
01268	B	0.0075	Long.	Fine Dimples	3 and 5	0.3 (2.1)	1.4 (10)
01268	B	0.0105	Long.	Fine Dimples	3 and 5	1.7 (12)	1.3 (9)
01268	B	0.0005	Long.	Fine Dimples	3 and 5	-104.1 (-718)	2.0 (14)
01268	B	0.0145	Long.	Fine Dimples	3 and 5	0.8 (6)	1.2 (8)

[a]See Figure 1.

Notes:

Residual stress data not corrected for layer removal stress relaxation and subsurface stress gradients.

Rad. = Radial

Long. = Longitudinal

9. References

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8. "Advances in X-ray Analysis." *Proceedings of the Annual Conference on Applications of X-ray Analysis*. Vol. 2–44, p. 1958, New York: Plenum Press, 2000.

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Appendix A. Servolink 01171 Bearing End Location A Residual Stress Depth Analysis Report

This appendix appears in its original form, without editorial change.

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================================ TEC Stress Analyzer v1.62 ===================
=================================== Depth Analysis ============================

Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01171
bearing end, location A, radial direction, 0 - 0.014" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60087.str
C:\STRESS\DATA\uh60090.str
C:\STRESS\DATA\uh60093.str
C:\STRESS\DATA\uh60096.str
C:\STRESS\DATA\uh60100.str
C:\STRESS\DATA\uh60103.str
C:\STRESS\DATA\uh60106.str
C:\STRESS\DATA\uh60109.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant : 4.08e-08

Depth	Psi = 0		Psi = 45			
inch	2-Th obs	2-Th true	2-Th obs	2-Th true	stress obs	stress true
0.0000	155.173	155.203	156.182	156.172	-92.88	-89.23
0.0005	155.104	155.120	156.214	156.216	-102.36	-100.96
0.0010	155.097	155.100	156.172	156.178	-99.13	-99.41
0.0020	155.085	155.080	156.176	156.178	-100.67	-101.38
0.0040	155.218	155.184	156.121	156.125	-83.20	-86.73
0.0070	155.963	155.935	156.036	156.039	-6.65	-9.46
0.0100	156.012	156.010	156.019	156.019	-0.62	-0.85
0.0140	156.021	156.020	156.015	156.016	0.46	0.41

Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness : 0.637 inch
Direction - X

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-89.23	1.6	2.0	-89.23
0.0005	-100.96	1.4	2.3	-100.66
0.0010	-99.41	1.3	2.2	-98.80
0.0020	-101.38	1.3	1.3	-100.13
0.0040	-86.73	1.3	0.9	-84.31
0.0070	-9.46	1.2	1.4	-6.15
0.0100	-0.85	1.2	1.5	2.54
0.0140	0.41	1.2	0.8	3.77

Servolink 01171 Bearing End Location A Residual Stress Depth Analysis Report

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Appendix B. Servolink 01171 Clevis End Location B Residual Stress Depth Analysis Report

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================================ TEC Stress Analyzer v1.62 ===================
=================================== Depth Analysis ===========================
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Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01171
clevis end, location B, longitudinal direction, 0 - 0.014" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60113.str
C:\STRESS\DATA\uh60116.str
C:\STRESS\DATA\uh60119.str
C:\STRESS\DATA\uh60122.str
C:\STRESS\DATA\uh60125.str
C:\STRESS\DATA\uh60128.str
C:\STRESS\DATA\uh60131.str
C:\STRESS\DATA\uh60134.str
C:\STRESS\DATA\uh60137.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant : 4.08e-08

Depth	Psi = 0		Psi = 45			
inch	2-Th obs	2-Th true	2-Th obs	2-Th true	stress obs	stress true
0.0000	155.154	155.168	156.179	156.177	-94.43	-92.92
0.0005	155.121	155.132	156.185	156.183	-98.12	-96.95
0.0010	155.104	155.114	156.191	156.192	-100.21	-99.37
0.0020	155.045	155.050	156.163	156.166	-103.35	-103.09
0.0030	155.052	155.028	156.151	156.153	-101.48	-104.00
0.0050	155.490	155.446	156.108	156.111	-56.64	-61.03
0.0070	155.879	155.853	156.067	156.069	-17.12	-19.66
0.0100	156.019	156.014	156.050	156.050	-2.77	-3.25
0.0140	156.017	156.017	156.055	156.055	-3.46	-3.44

Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness : 0.382 inch
Direction - X

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-92.92	1.7	0.4	-92.92
0.0005	-96.95	1.4	1.1	-96.45
0.0010	-99.37	1.3	1.7	-98.36
0.0020	-103.09	1.3	2.0	-101.02
0.0030	-104.00	1.3	1.9	-100.85
0.0050	-61.03	1.3	2.5	-56.17
0.0070	-19.66	1.2	2.0	-13.98
0.0100	-3.25	1.1	0.2	2.72
0.0140	-3.44	1.1	2.0	2.59

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Appendix C. Servolink 01266 Bearing End Location C Residual Stress Depth Analysis Report

This appendix appears in its original form, without editorial change.

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==================================== TEC Stress Analyzer v1.62 ====================
==================================== Depth Analysis ============================

Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01266
bearing end, location C, radial direction, 0 - 0.014" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60196.str
C:\STRESS\DATA\uh60198.str
C:\STRESS\DATA\uh60200.str
C:\STRESS\DATA\uh60202.str
C:\STRESS\DATA\uh60204.str
C:\STRESS\DATA\uh60206.str
C:\STRESS\DATA\uh60208.str
C:\STRESS\DATA\uh60210.str
C:\STRESS\DATA\uh60212.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant : 4.08e-08

Depth	Psi = 0		Psi = 45			
inch	2-Th obs	2-Th true	2-Th obs	2-Th true	stress obs	stress true
0.0000	155.139	155.142	156.211	156.211	-98.75	-98.44
0.0005	155.130	155.132	156.210	156.204	-99.44	-98.75
0.0010	155.130	155.134	156.249	156.245	-103.05	-102.25
0.0020	155.087	155.097	156.224	156.226	-104.81	-104.01
0.0040	154.983	154.967	156.225	156.227	-114.80	-116.38
0.0060	155.369	155.320	156.180	156.186	-74.41	-79.57
0.0080	155.908	155.875	156.064	156.069	-14.25	-17.60
0.0110	156.011	156.007	156.067	156.067	-5.11	-5.49
0.0140	156.017	156.017	156.056	156.057	-3.56	-3.64

Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness : 0.631 inch
Direction - X

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-98.44	1.8	3.0	-98.44
0.0005	-98.75	1.5	1.6	-98.44
0.0010	-102.25	1.4	2.1	-101.62
0.0020	-104.01	1.3	1.7	-102.72
0.0040	-116.38	1.4	1.9	-113.70
0.0060	-79.57	1.3	2.1	-75.65
0.0080	-17.60	1.2	0.7	-13.08
0.0110	-5.49	1.2	0.6	-0.78
0.0140	-3.64	1.2	0.2	1.12

Servolink 01266 Bearing End Location C Residual Stress Depth Analysis Report

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Appendix D. Servolink 01266 Clevis End Location B Residual Stress Depth Analysis Report

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==================== TEC Stress Analyzer v1.62 ====================
==================== Depth Analysis ====================

Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01266
clevis end, location B, longitudinal direction, 0 - 0.0145" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60141.str
C:\STRESS\DATA\uh60144.str
C:\STRESS\DATA\uh60148.str
C:\STRESS\DATA\uh60152.str
C:\STRESS\DATA\uh60156.str
C:\STRESS\DATA\uh60160.str
C:\STRESS\DATA\uh60164.str
C:\STRESS\DATA\uh60168.str
C:\STRESS\DATA\uh60172.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant : 4.08e-08

Depth	Psi = 0		Psi = 45			
inch	2-Th obs	2-Th true	2-Th obs	2-Th true	stress obs	stress true
0.0000	155.228	155.257	156.225	156.213	-91.63	-87.88
0.0005	155.162	155.179	156.267	156.261	-101.60	-99.45
0.0015	155.134	155.140	156.266	156.267	-104.10	-103.71
0.0025	155.112	155.118	156.250	156.251	-104.77	-104.36
0.0035	155.082	155.086	156.247	156.250	-107.39	-107.20
0.0055	155.052	155.024	156.173	156.179	-103.52	-106.69
0.0075	155.605	155.559	156.086	156.090	-44.02	-48.67
0.0105	156.055	156.040	156.025	156.026	2.73	1.21
0.0145	156.017	156.019	156.016	156.016	0.13	0.29

Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness : 0.384 inch
Direction - X

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-87.88	1.8	0.2	-87.88
0.0005	-99.45	1.4	1.0	-98.96
0.0015	-103.71	1.3	2.4	-102.16
0.0025	-104.36	1.2	2.0	-101.74
0.0035	-107.20	1.3	1.2	-103.47
0.0055	-106.69	1.3	0.9	-100.75
0.0075	-48.67	1.4	1.6	-41.14
0.0105	1.21	1.3	1.6	9.41
0.0145	0.29	1.2	1.7	8.32

Servolink 01266 Clevis End Location B Residual Stress Depth Analysis Report

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Appendix E. Servolink 01268 Bearing End Location D Residual Stress Depth Analysis Report

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================================ TEC Stress Analyzer v1.62 ===================
=================================== Depth Analysis ===========================

Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01268
bearing end, location D, radial direction, 0 - 0.0145" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60175.str
C:\STRESS\DATA\uh60179.str
C:\STRESS\DATA\uh60181.str
C:\STRESS\DATA\uh60183.str
C:\STRESS\DATA\uh60185.str
C:\STRESS\DATA\uh60187.str
C:\STRESS\DATA\uh60189.str
C:\STRESS\DATA\uh60191.str
C:\STRESS\DATA\uh60193.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant : 4.08e-08

Depth	Psi = 0		Psi = 45			
inch	2-Th obs	2-Th true	2-Th obs	2-Th true	stress obs	stress true
0.0000	155.155	155.165	156.122	156.101	-89.21	-86.37
0.0005	155.132	155.138	156.195	156.184	-97.97	-96.39
0.0015	155.123	155.132	156.206	156.207	-99.79	-99.05
0.0025	155.054	155.058	156.188	156.190	-104.66	-104.45
0.0040	155.099	155.064	156.173	156.177	-99.11	-102.75
0.0060	155.696	155.651	156.094	156.099	-36.34	-40.88
0.0085	156.002	155.988	156.047	156.049	-4.16	-5.55
0.0110	156.017	156.016	156.044	156.045	-2.48	-2.55
0.0140	156.009	156.010	156.033	156.034	-2.20	-2.20

Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness : 0.631 inch
Direction - X

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-86.37	1.8	0.8	-86.37
0.0005	-96.39	1.4	0.7	-96.10
0.0015	-99.05	1.3	2.9	-98.14
0.0025	-104.45	1.3	2.2	-102.89
0.0040	-102.75	1.3	2.7	-100.21
0.0060	-40.88	1.2	3.0	-37.44
0.0085	-5.55	1.2	0.3	-1.76
0.0110	-2.55	1.2	1.0	1.28
0.0140	-2.20	1.1	0.7	1.65

Servolink 01268 Bearing End Location D Residual Stress Depth Analysis Report

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Appendix F. Servolink 01268 Clevis End Location B Residual Stress Depth Analysis Report

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=============================== TEC Stress Analyzer v1.62 ===================
================================== Depth Analysis ==========================

Sample Description:
UH-60 Blackhawk Helicopter Servo Link, P/N 70400-08110-061, S/N 01268
clevis end, location B, longitudinal direction, 0 - 0.0145" depth

*** All stresses are shown in KSI ***

File names:
C:\STRESS\DATA\uh60140.str
C:\STRESS\DATA\uh60142.str
C:\STRESS\DATA\uh60146.str
C:\STRESS\DATA\uh60150.str
C:\STRESS\DATA\uh60154.str
C:\STRESS\DATA\uh60158.str
C:\STRESS\DATA\uh60162.str
C:\STRESS\DATA\uh60166.str
C:\STRESS\DATA\uh60170.str

Gradient correction:
Mass absorption coefficient: 2277.80
Lambda for target material : 2.28970
Material elastic constant  : 4.08e-08
```

Depth inch	Psi = 0 2-Th obs	Psi = 0 2-Th true	Psi = 45 2-Th obs	Psi = 45 2-Th true	stress obs	stress true
0.0000	155.187	155.212	156.242	156.237	-97.02	-94.22
0.0005	155.130	155.146	156.261	156.258	-104.10	-102.27
0.0015	155.090	155.095	156.266	156.265	-108.29	-107.82
0.0025	155.088	155.090	156.269	156.270	-108.79	-108.64
0.0035	155.069	155.046	156.256	156.263	-109.44	-112.17
0.0055	155.528	155.477	156.096	156.104	-52.01	-57.53
0.0075	156.017	155.990	156.014	156.016	0.30	-2.42
0.0105	156.049	156.049	156.030	156.030	1.70	1.67
0.0145	156.027	156.028	156.018	156.018	0.85	0.91

```
Layer removal correction (including stress gradient correction); Flat plate.
Plate thickness  :   0.385 inch
Direction - X
```

Depth inch	Stress	Counting Statistics Error	Probable Error	Stress true
0.0000	-94.22	1.7	0.7	-94.22
0.0005	-102.27	1.3	2.0	-101.76
0.0015	-107.82	1.4	1.8	-106.22
0.0025	-108.64	1.4	1.7	-105.91
0.0035	-112.17	1.3	1.4	-108.31
0.0055	-57.53	1.4	2.2	-51.92
0.0075	-2.42	1.2	1.4	3.77
0.0105	1.67	1.2	1.3	7.80
0.0145	0.91	1.2	0.5	6.89

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13. ABSTRACT*(Maximum 200 words)*

The Processing and Properties Branch of the U.S. Army Research Laboratory's (ARL) Weapons and Materials Research Directorate examined the shot-peened surfaces of three UH-60 Blackhawk utility helicopter servolinks. It was purported that the surfaces of the components were damaged from a prior manufacturing operation. ARL performed visual and stereoscopic examination of the surface, measured the depth of some scratches, and quantified the residual stresses at the surface through x-ray diffraction in order to characterize the suspect components. In most cases, the scratches were shown to be present prior to the shot-peening operation. It was concluded that the parts exhibited evidence of overall peening, and the surface residual stresses were compressive and acceptable in areas varying in the degree of peening (i.e., pronounced peening dimples vs. less pronounced dimples).

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